Carderock Division
Naval Surface Warfare Center
West Bethesda, MD 20817-5700

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Survivability, Structures, and Materials Directorate

Technical Report

Evaluation of PPT-2 Flux-Cored Titanium Weldment

by

Michael E. Wells

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A titanium weldment fabricated in 1/2-inch thick commercially pure plate with the PPT-2 flux-cored wire was obtained from The Paton Institute for evaluation. The results of nondestructive inspection showed that the flux cored wire and welding procedures used to produce the weldment resulted in a sound weld with no indications of cracking or other internal defects. Chemical analysis showed acceptable carbon, hydrogen, iron and oxygen content for Ti-CP, grade 2 weld metal per ASTM B265. The nitrogen content of the weld deposit was well in excess of the specification allowable. The yield strength and elongation properties of the weldment did not meet the specification requirements of ASTM B265 for Ti-CP, grade 2 plate. A single bend ductility test failed to meet the 2T radius bend requirement of NAVSEA technical publication S9074-AQ-GIB-010/248. The elevated tensile and yield strength properties and low elongation are attributed to nitrogen contamination of the weld deposit. Interstitial contamination of the weld is believed to have occurred from the absorption of nitrogen into the weld puddle. This is based on the absence of a hardened surface layer which would be indicative of interstitial absorption through the slag covering into the solidified weld.

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ABSTRACT

A titanium weldment fabricated in 1/2-inch thick commercially pure plate with the PPT-2 flux-cored wire was obtained from the Paton Welding Institute, Kiev, Ukraine for evaluation. The results of nondestructive inspection showed that the flux cored wire and welding procedures used to produce the weldment resulted in a sound weld with no indications of cracking or other internal defects. Chemical analysis showed acceptable carbon, hydrogen, iron and oxygen content for Ti-CP, grade 2 weld metal per ASTM B265. The nitrogen content of the weld deposit was well in excess of the specification allowable. The yield strength and elongation properties of the weldment did not meet the specification requirements of ASTM B265 for Ti-CP, grade 2 plate. A single bend ductility test failed to meet the 2T radius bend requirement of NAVSEA technical publication S9074-AQ-GIB-010/248. The elevated tensile and yield strength properties and low elongation are attributed to nitrogen contamination of the weld deposit. Interstitial contamination of the weld is believed to have occurred from the absorption of nitrogen into the weld puddle. This is based on the absence of a hardened surface layer, which would be indicative of interstitial absorption through the slag covering into the solidified weld.

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ADMINISTRATIVE INFORMATION

This report was prepared as part of the Seaborne Materials Program under the sponsorship of Dr. George Yoder, Office of Naval Research, (ONR 332), Arlington, VA. The work was supervised by Mr. Robert DeNale, Head, Welding and Non-Destructive Evaluation (NDE) Branch, NSWC Carderock Division (Code 615). West Bethesda, MD.

INTRODUCTION

While there are many fusion welding processes in general use for titanium, the gas tungsten arc welding (GTAW) process is used exclusively for joining thin section titanium seawater piping systems on U.S. Navy surface ships. The selection of GTAW is driven by its precise control of welding parameters and excellent control of root pass weld penetration. In addition, the process produces high quality welds, it is free of the spatter that may occur with gas metal arc welding, and can be used with or without filler material depending on the specific application.

The techniques and equipment used in GTAW of titanium piping components are similar to those employed for other high performance ship materials such as stainless steel and Cu-Ni alloys. However, titanium is an extremely reactive material. At elevated temperatures, titanium will readily absorb oxygen and nitrogen from the surrounding atmosphere to the detriment of weld metal properties. These reactions are particularly rapid when titanium is molten; hence, the weld pool is most vulnerable to embrittlement. To prevent atmospheric contamination during the welding process, complete inert gas shielding of both the weld pool and the hot solidified weld is required at temperatures above about 840° F [1]. Back shielding of the weld joint as well as torch and trailing shields are required.

Only the inert gases argon, helium or argon/helium mixtures are used in titanium welding to protect against the absorption of interstitial elements. The torch shielding gas provides primary shielding of the liquid weld pool. For open air welding in a shipyard environment, a trailing shield is attached to the welding torch. These devices provide secondary shielding of the solidified weld and adjacent heat-affected- zone (HAZ) during cooling. The size and shape of the trailing shield depends on the welding speed and geometry of the component. For titanium piping systems, trailing shields are generally custom made by shipyard personnel to match each pipe diameter. The underside of the weld must also be protected with an inert gas. For pipe configurations, the inside must be fully purged prior to welding. For small piping subassemblies, the gas can be confined within the pipe by sealing both ends. For large diameter pipe or long piping runs, dams or other devices are placed inside the pipe to contain the backside purge gas.

The surface color of the as-deposited weld is an indicator of shielding effectiveness and, indirectly, the quality of the weld. With proper shielding, the color of the oxide film (TiO_2) that forms on titanium after solidification is a bright and lustrous silver color. The absorption of oxygen from impurities in the shielding gas or inadequate gas shielding of the weld joint will thicken the oxide film, which changes color from light refraction. The color of the oxide layer changes as a function of increasing oxide thickness from silver to shades of straw, purple, blue, yellow, dull gray and powder white. Surface color is used by the Naval Sea Systems Command (NAVSEA) as the

acceptance criteria for visual examination of titanium welds on U.S. Navy surface ships. However, it is noted that it is possible to produce a visually acceptable silver colored weld if a contaminated weld pool (i.e. defective torch gas) is well shielded after it solidifies.

Prior Navy work has shown that the major cost driver in titanium fabrication is the repair/rework of air contaminated welds. To minimize the potential for interstitial contamination, NAVSEA technical publication S9074-AQ-GIB-010/278 [2] imposes additional requirements on shipyard personnel engaged in welding of titanium components. These requirements include weld joint design controls to ensure the accessibility of inert gas shielding equipment, shipyard facility modifications to minimize the potential effects of winds and drafts on inert gas shielding, periodic dewpoint measurements to ensure gas purity, and surface color inspections to gage shielding effectiveness.

An alternative to inert gas shielding is the use of a layer of molten flux. The molten flux behaves like a blanket physically separating the weld pool from the environment. Joining processes such as flux-cored arc welding, submerged arc welding and shielded metal arc welding all take advantage of the protection provided by the molten flux layer. In commercial shipyards, flux-cored arc welding is the process of choice due to the combination of process parameter control and the deposition of a slag layer during welding, which shields the molten liquid from atmospheric contamination. The development of a flux-cored wire for titanium offers the potential for significant welding cost reduction through the elimination of cumbersome and labor intensive shielding and inspection requirements currently imposed on shipyard personnel. While the present level of titanium technology in the U.S. has not developed a flux-cored wire, extensive research in the Former Soviet Union (FSU) has reportedly resulted in the development of both paste fluxes and flux-cored wires for GTAW of thin-section titanium [3].

PASTE FLUX AND FLUX-CORED WIRE DEVELOPMENT

Welding fluxes for titanium must protect the weld pool and solidified weld from atmospheric contamination at temperatures above about 840° F. They must also provide a stable arc and be thermodynamically stable at welding temperatures in the presence of liquid titanium. This latter requirement eliminates oxide-based fluxes developed for ferrous welding, as they would be reduced by titanium and result in unacceptably high oxygen concentrations in the weld zone. In addition, the hydration rate of the flux in moist atmospheres should be low to minimize contamination with interstitial elements. These requirements have limited titanium flux development work to the various fluorides and chlorides of alkaline, alkaline earth and rare earth metals [3]. Halides that are thermodynamically stable up to 2500° K in the presence of liquid titanium include NaCl, KCl, $CaCl_2$, $BaCl_2$, CaF_2, and BaF_2 [4]. Fluorides are preferred to chlorides on the basis of moisture absorption [4]. Calcium fluoride has the highest melting point (1364° C) of

the metal halides and has served as the basis in the formulation of fluxes for gas tungsten arc welding of titanium, as well as for other flux assisted welding processes.*

A limited amount of work has been performed in the U.S. in the area of flux-cored wire development by Eager and associates at MIT [5]. This work was in connection with a submerged arc welding process development program for titanium and involved the addition of sodium and potassium chlorides to the weld puddle by means of a tubular electrode. The electrode extended through a submerged arc welding flux covering of CaF_2. The baseline submerged arc welds demonstrated that an acceptable oxygen content of 1000-1200 ppm could be obtained using an optical purity CaF_2 flux covering, but produced unacceptable nitrogen concentrations of 440-810 ppm. Chloride additions to the CaF_2 flux by means of the tubular electrode elevated the oxygen content to 1200-1700 ppm but reduced the nitrogen content of the weld deposit to 120-430 ppm.

Most of the foreign literature dealing with the formulation of paste fluxes and flux-cored wires for gas tungsten arc welding of titanium has been published in the FSU by S.M. Gurevich and co-workers at The Paton Institute, Kiev, Ukraine. According to the published technical papers, their results have been good, but the exact compositions of their welding fluxes and chemical composition of the weld deposits are often not reported. The FSU paste fluxes for GTAW of titanium are based on CaF_2 or SrF_2 in combination with fluorides and/or chlorides of magnesium, lithium and other alkaline, alkaline earth and rare earth metals [6-11]. The halide pastes (composed of flux powder and alcohol) are applied to the joint surfaces prior to welding and used in conjunction with a square groove joint design. When the arc reaches the layer of flux on the surface of the joint, the arc plasma is constricted. The more focused arc plasma emanating from the tip of the tungsten electrode concentrates the arc heat in a smaller region, increasing weld penetration (>2X) and decreasing weld width [7, 12-14]. No degradation in mechanical or corrosion properties of GTAW flux welds has been reported and the paste fluxes have been used in commercial applications to join up to 1/2-inch thick titanium in a single pass [6,15]. However, the FSU paste fluxes are designed specifically to enhance penetration and require some type of supplementary shielding to prevent atmospheric contamination of the fusion zone [9-11].

Specific information on flux-cored wires for GTAW of titanium is limited, reflecting the proprietary nature of these products. Two flux-cored wires were developed by Gurevich and co-workers at The Paton Institute. The wires were designated as PPT-1 and PPT-2. In addition, Gurevich has US Patent 4,131,493 "Flux-Cored Welding Wire" [16]. The PPT-1 flux-cored wire is based on CaF_2 in combination with sodium fluoride and barium chloride, and is designed for thin section welding (<3/8 inch) of titanium in a

* Extensive work has been performed in the FSU on the development of fluxes for submerged arc and electroslag welding of thick-section titanium. These fluxes are based on CaF_2 in combination with other halide metals. Experimental fluxes have also been developed in the U.S. for thick-section welding of titanium by these same processes. Much of the flux development work performed in the U.S. has been based upon earlier published findings from the FSU.

single pass. The PPT-2 flux-cored wire is also based on CaF_2 in combination with fluorides of lanthanum or cerium, barium and strontium, and is designed for welding thicker section titanium (up to 5/8-inch) in a single pass. The addition of the rare earth elements, lanthanum or cerium, is reported to improve the impact strength of the weld deposit [16]. In operation, the wires produce a layer of slag that covers the solidified weld and adjacent heat-affected-zone. The slag covering produced by the PPT-1 wire is removed by wire brushing, while the slag produced with the PPT-2 wire is reported to be more easily removed by scraping [16]. The PPT-1 flux-cored wire was used to fabricate welds in Al and Al-V titanium plates of 1/4-inch thickness in a single pass. The tensile and ductility properties of the welds were comparable to those of the baseplate materials [17-18]. No information was available on the mechanical properties of PPT-2 flux-cored weldments.

SCOPE

Through the collaborative efforts of Army and Navy personnel, a small Ti-CP weldment fabricated with the PPT-2 wire was obtained from the FSU in FY99. The objective of the work reported herein was to evaluate the chemical and mechanical properties of the FSU weldment to help assess the potential of developing flux-cored wires for use in titanium shipyard fabrication. Information is provided on interstitial chemical analysis, hardness profiles, tensile and ductility properties and bend properties of the weld deposit.

PROCEDURE

MATERIALS

The chemical composition and mechanical properties of the 1/2-inch thick plate material are provided in Tables 1 and 2, respectively, along with ASTM specification requirements for comparison. The material meets the chemical and mechanical property requirements for Ti-CP, grade 2 per ASTM B265 [19].

Table 1. Chemical composition of baseplate and specification requirements.

Material	Composition, weight %				
	N	C	H	Fe	O
Plate*	0.013	0.016	0.0016	0.23	0.132
ASTM B265, Gr. 1	0.03 max	0.08 max	0.015 max	0.20 max	0.18 max
ASTM B265, Gr. 2	0.03 max	0.08 max	0.015 max	0.30 max	0.25 max
*Analysis by Luvak Inc.					

Table 2. Tensile properties of baseplate and specification requirements.

Material	Tensile Strength ksi	Yield Strength ksi	Elongation %
Plate*	75	58	not reported
ASTM B265, Gr. 1	35 min	25 min/45 max	24 min
ASTM B265, Gr. 2	50 min	40 min/65 max	20 min
*Manufacturer's analysis			

The exact composition of the flux cored wire was not available. The PPT-2 composition from reference 16 is given as 40-50% CaF_2, 18-20% LaF_3 or CeF_3, 5-10% BaF_2 and SrF_2 (remainder). No information was available on the composition of the wire sheath, which may be produced from commercially pure titanium or one of its alloys [16].

WELDMENT PREPARATION

Two plate sections approximately 1/2- T x 6- W- x 6-inches L were butted together to form a 90-degree square groove joint. A backing bar was used to allow for welding from one side. No other details on joint preparation or the possible use of auxiliary shielding were available [20]. The weldment was fabricated by personnel at The Paton Institute using the gas tungsten arc welding process with the PPT-2 flux-cored filler wire. The weldment was completed in a single pass at a welding current of 450 amperes, a voltage of 18 volts and a travel speed of ~5 inches/min. The calculated heat input was 97.2 kJ/in.

EVALUATION

The flux-cored weldment was evaluated by the methods described below:

- Nondestructive evaluation, including visual and radiographic inspection, in accordance with the requirements of NAVSEA Technical publicationT9074-AS-GIB-010/271 [21]. Visual inspection for surface color was performed in accordance with the requirements of NAVSEA Technical Publication S9074-AQ-GIB-010/248 [22].
- Macro and micrographic examination of the weld metal. Macrospecimens were mounted, polished and swabbed with an etchant of 50 ml H_2O + 20 ml HF + 20 ml HCl for 3-5 minutes and rinsed in distilled water. An etchant of 50 ml H_2O + 4 ml HNO_3 + 2 ml HF was used to reveal the microstructure.
- Chemical analyses for interstitial and iron content of the baseplate and weld metal.
- Diamond pyramid hardness (DPH) measurements across the baseplate, heat-affected zone and weld metal at a load of 500 grams. The DPH

measurements were converted to Rockwell B scale measurements for reporting purposes.

- An all weld metal tensile test using a 0.250-inch diameter subsize specimen with a 1-inch gage length. The specimen was tested in accordance with ANSI/AWS B4.0-98 [23].
- Standard transverse bend specimens of 3/8-inch thickness tested in accordance with ANSI/AWS B4.0-98 [23] at a bend radius of 2T, 3T and 4T. The acceptance criterion was based on the requirements of NAVSEA technical publication S9074-AQ-GIB-010/248 [22].

RESULTS AND DISCUSSION

NONDESTRUCTIVE EVALUATION

Visual examination of the weld surface did not reveal any indications of brushing and grinding, and the surface appeared to be in an "as-deposited" condition, Figure 1. The color of the weld surface was a lustrous silver color. As noted previously, oxygen contamination of the solidified weld will produce surface discoloration as the oxide layer thickens. The absence of surface color indicates that the slag covering effectively shielded the solidified weld from oxygen contamination (assuming a trailing shielded was not used). A slight degree of underfill was observed along the fusion line on each side of the weld. Radiographic inspection revealed no indications of cracking, porosity or incomplete fusion in the weld or along the sidewalls of the joint.

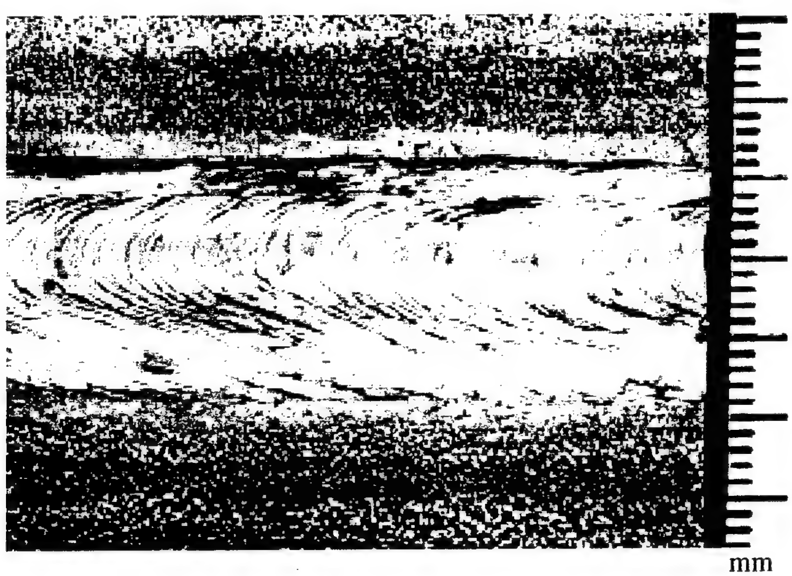

Figure 1. Surface appearance of PPT-2 flux-cored weldment.

MACRO AND MICROGRAPHIC EXAMINATION

A macrosection from the flux-cored weldment is provided in Figure 2. The macrostructure shows a single weld pass that is characterized by the formation of large columnar grains that initiate at the solid/liquid interface. The relatively wide HAZ is attributed to the high heat input (97kJ/in) used in fabrication of the weldment. The aspect ratio (weld depth to width) is provided in Table 3, along with typical values for conventional gas tungsten arc welds in Ti-CP using the same parameters and joint design as employed in fabrication of the flux-cored weldment. A comparison of the weld bead dimensions shows that the flux formulation was effective in increasing weld penetration as compared with conventional GTAW of titanium with argon shielding. The increase in weld penetration is on the order of 2X.

Figure 2. Macrosection from flux-cored weldment

Table 3. Flux-cored weld bead dimensions.

Material	Weld Width mm	Depth of Penetration, mm	Aspect Ratio
Flux-Cored Weld	16	13.5	0.8
Conventional Weld	15	6	0.4

The weld metal microstructure is shown in Figure 3, and is typical of microstructures that form in Ti-CP weld metal on cooling from above the beta transus. The structure consists predominantly of coarse acicular alpha along with evidence of prior beta grain boundaries. Acicular alpha forms in titanium by a nucleation and growth process and can exist as fine or thick plates depending on the weld metal cooling rate. The coarse alpha platlets shown in Figure 3 are attributed to a slow cooling rate

resulting from the high heat input used in fabrication of the flux-cored weldment. There was some evidence of serrated alpha, characterized by irregular grain size and jagged grain boundaries, that forms in commercially pure titanium weld metal of high purity.

Figure 3. Microstructure of PPT-2 weld deposit.

CHEMICAL ANALYSIS

The chemical composition of the weld deposit is provided in Table 4, along with the chemical requirements from ASTM B265 [19] for Ti-CP grade 2 plate.* The weld deposit meets the chemical composition requirements for all elements except nitrogen, which is significantly higher than the specification allowable. While the extent of interstitial and iron pickup is unknown due to the lack of information on the wire chemistry, nitrogen contamination of the weld with the CaF_2 based flux is consistent with the U.S. literature [5].

Table 4. Chemical composition of PPT-2 weld deposit.

Material	Composition, weight %				
	N	C	H	Fe	O
PPT-2 Weld	0.071	0.016	0.0017	0.20	0.159
ASTM B265, Gr. 2	0.03 max	0.08 max	0.015 max	0.30 max	0.25 max

* Because weld metal chemistry is not specified in the titanium filler material specifications, the weld metal must meet the maximum chemical composition requirements of the base material.

HARDNESS MEASUREMENTS

Diamond pyramid hardness measurements were taken just below the weld surface and through the weld thickness, in addition to measurements in the HAZ and baseplate material. These measurements were converted to Rockwell B scale and are provided in Table 5. The hardness values taken in both directions in the weld are essentially the same. With regard to nitrogen contamination of the weld, it is expected that the diffusion of nitrogen through the slag covering would produce a hardened surface layer. The absence of such a layer indicates that nitrogen absorption likely occurred as a result of diffusion into the liquid puddle.

Table 5. Rockwell B hardness values of flux-cored weldment.

Rockwell B*	Weld		HAZ	Plate
	Subsurface	Thickness		
Minimum	89.2	88.3	86.0	86.0
Maximum	94.4	94.4	91.7	90.4
Mean	92.0	91.5	89.7	88.7
Count	6	13	14	10
*Converted from DPH measurements				

TENSILE PROPERTIES

The tensile test data from the all weld metal specimen is provided in Table 6. The tensile requirements from ASTM B265 [19] for Ti-CP grade 2 plate are provided for comparison.* The yield strength of the weld metal exceeded the maximum allowable and the elongation failed to meet the minimum requirement of 20%.

The elevated strength properties of the flux-cored weldment are attributed primarily to the nitrogen content of the weld deposit, as this element is a potent strengthener in titanium. Despite the elevated strength properties, the ductility of the weld, as measured by elongation and reduction in area, was 16% and 33%, respectively. Although the ASTM plate specification does not require a minimum reduction in area (R/A) value, it is noted that the reduction in area of the Ti-CP flux-cored weld metal satisfies the minimum R/A requirement of 30% for Ti-CP, grade 2 forgings per ASTM 381 [24].

* Because weld metal tensile requirements are not specified in the AWS titanium filler material specifications, the weld metal must meet the minimum tensile requirements of the base material.

Table 6. Tensile properties of PPT-2 weld metal.

Material	Tensile Strength, ksi	Yield Strength, ksi	Elongation %	Reduction in Area, %
Weld	92	79	16	33
ASTM B265, Gr. 2	50 min	40 min/65 max	20 min	none

BEND TEST

The results of bend ductility tests are provided in Table 7, along with the bend test requirements from reference 23 for comparison. For welded titanium materials on U.S. Navy surface ships, the bend radius is determined in accordance with ANSI/AWS B4.0 using the minimum base metal elongation. The minimum elongation requirement for Ti-CP grade 2 materials is 20%, hence, the bend radius is 2T over a 180° bend, where T is equal to the specimen thickness. The bend specimen tested at 2T failed due to the presence of a 1/4-inch long open defect at the fusion line of the specimen, Figure 4. A second specimen was tested at 4T over a 180° bend and passed as shown in Figure 5. It is noted that ASTM B265 [19] requires a 4T bend over 105° for Ti-CP, grade 2 material.

Table 7. Bend tests of flux-cored weldment.

	Bend Radius	Pass/Fail
Specimen 1	2T	Failed
Specimen 2	4T	Passed
S9074-AQ-GIB-010/248	2T	No open defects > 1/8-inch*
* NAVSEA technical publication S9074-AQ-GIB-010/248 [23]		

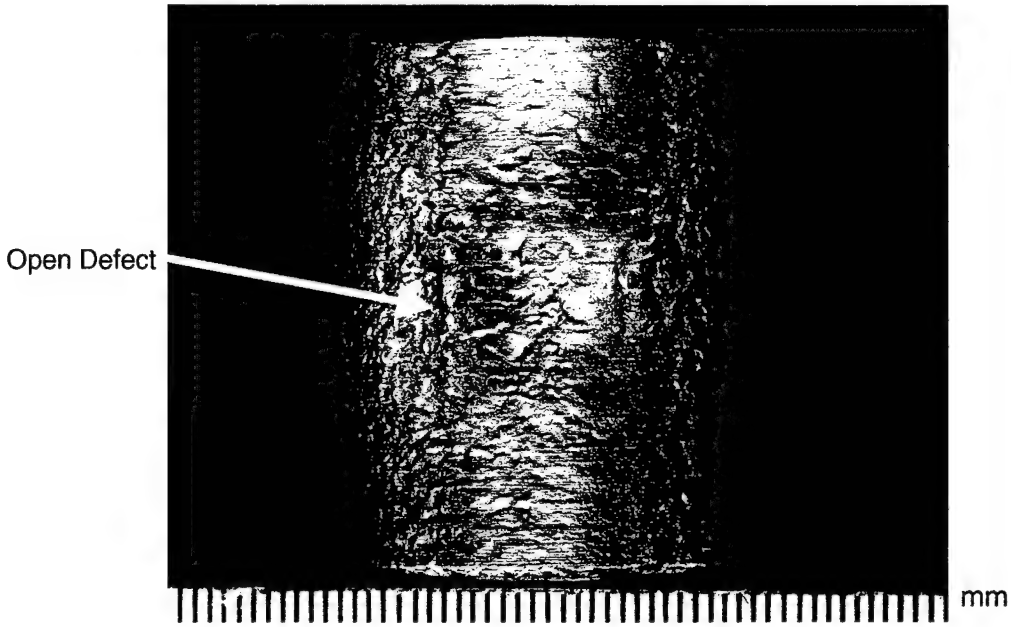

Figure 4. Transverse 2T face bend.

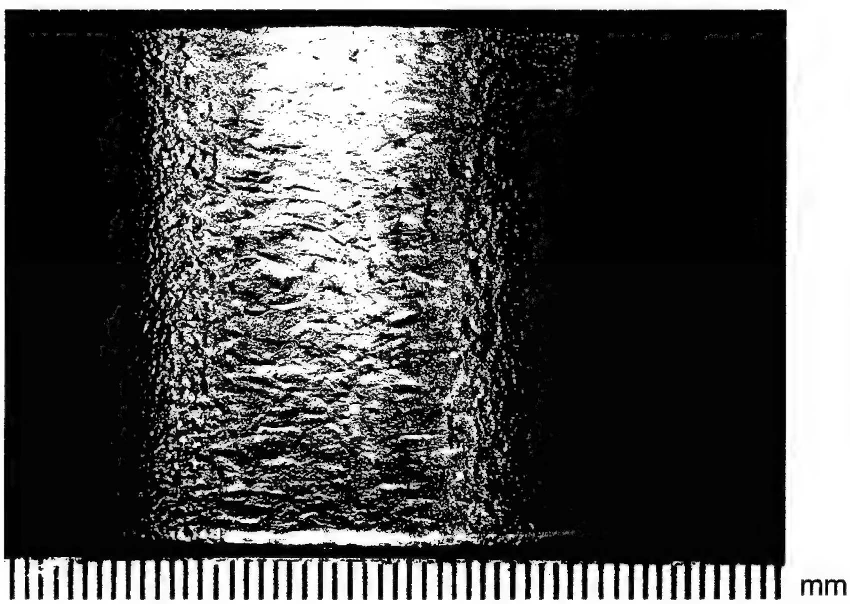

Figure 5. Transverse 4T face bend.

SUMMARY

A titanium weldment fabricated in 1/2-inch thick commercially pure plate with the PPT-2 flux-cored wire was obtained from The Paton Institute for evaluation. The results of nondestructive inspection showed that the flux cored wire and welding procedures used to produce the weldment resulted in a sound weld with no indications of cracking or other internal defects. Chemical analysis of the weld metal showed acceptable carbon, hydrogen, iron and oxygen content in accordance with the plate chemistry requirements of ASTM B265, grade 2. The nitrogen content of the weld deposit was well in excess of the specification allowable. The yield strength and elongation properties of the weldment did not meet the specification requirements of ASTM B265 for Ti-CP, grade 2 plate. A single bend ductility test failed to meet the 2T radius bend requirement of NAVSEA technical publication S9074-AQ-GIB-010/248. The elevated tensile and yield strength properties and low elongation are attributed to nitrogen contamination of the weld deposit. Interstitial contamination of the weld is believed to have occurred from the absorption of nitrogen into the weld puddle. This is based on the absence of a hardened surface layer, which would be indicative of interstitial absorption through the slag covering into the solidified weld.

FUTURE WORK

Based on the results of this investigation, future work will focus on the development of a flux-cored wire for GTAW of Ti-CP, grade 2 with acceptable interstitial content. Initial efforts will be directed toward an examination of the effects of chlorine additions to reduce the nitrogen content of the weld deposit.

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